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Relationships between urbanization and the oak resource of the Minneapolis/St. Paul Metropolitan area from 1991 to 1998

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Abstract

Urbanization was associated with loss and transformation of the oak forest in the Twin Cities (Minneapolis and St. Paul) metropolitan area (TCMA) over a recent 7-year interval. Between 1991 and 1998, urbanization increased based on several indicators: population density, area of developed land, and area of impervious surface—total impervious area and area within three classes of increasing degree of imperviousness (protected, affected, and degraded). We quantified relationships between changes in urbanization and changes in several parameters describing the oak forest at the scale of ecological subsection. Increased total and affected impervious area were strongly correlated with decreased area of oak forest when changes of the urbanization indicators and oak were expressed as percentages of the subsection area. Relationships were reversed when changes were expressed as percentages of the 1991 values. Increased population density was strongly correlated with increased loss in numbers and increased isolation of oak patches, but weakly correlated with loss of oak forest area. This is the first study to quantify relationships between changes in urbanization and changes in a specific forest cover type. Our results demonstrate complexities of urbanization impacts on a metropolitan forest resource, and highlight the importance of selected variables, spatial and temporal scales, and expressions of change when quantifying these relationships.
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Keywords: Urban indicator; Quercus; Impervious surface; Developed land; Population; Forest; Patch

1. Introduction

Forests in metropolitan areas account for almost one-fourth of the total tree canopy cover in the 48 conterminous states of the USA (Dwyer et al., 2000). These forests perform a variety of ecological services and offer numerous social amenities. They provide food and habitat for animals, conserve energy, protect watersheds, improve air quality, abate noise pollution, and perhaps even reduce the effects of global warming by sequestering carbon (McPherson et al., 1997; Nowak and Crane, 1998; American Forests, 2000). In addition, forests in metropolitan areas provide recreational and educational opportunities for urban and suburban dwellers.

Ironically, even though forests in metropolitan areas are increasingly acknowledged for their role in improving the quality of the urban environment, rapid urbanization in wildland–urban interface areas and redevelopment in existing urban areas are impacting their existence, structure and health. This general perception is based on anecdotal observations as well as on a number of studies on urbanization impacts on forest vegetation. In the late 1800s, forests covered an estimated 70% of the Minnesota cities of St. Paul and Minneapolis and the surrounding area (Minnesota Department of Natural Resources, 1994). By 1990, only 8.5% of this area was covered by forest, about half of which was oak (Ward and Juzwik, 2005; Minnesota Department of Natural Resources, 1996). The two cities and the surrounding area, collectively referred to as the Twin Cities metropolitan area (TCMA), are in the throes of rapid urban expansion as well as restoration and redevelopment in older parts of the cities and first ring suburbs. From 1990 to 2000, the TCMA had the greatest population increase in its history. There were 353,000 (15.4%) more people and almost 146,000 (16.7%) more households in 2000 than in 1990 (Metropolitan Council, 2006).

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Gradient studies are one of the most common designs for assessments of urban impacts on forests. An urban-to-rural gradient can be created by establishing plots along a transect at increasing distances from an urban core (Medley et al., 1995) or by establishing plots in different land use/land cover classes that range from non-developed to a high intensity of development. Differences in land use/land cover are assessed at one point in time (Guntenspergen and Levenson, 1997; Iverson and Cook, 2000; Porter et al., 2001) or at two or more points in time (Sharpe et al., 1986; Zipperer, 1993; MacLean and Bolsinger, 1997; Lo and Yang, 2002). While land use/land cover is itself an indicator of both urbanization and forest land, more specific measures of urbanization are often included, such as area covered with pavement or buildings (Porter et al., 2001), level of human activity (Guntenspergen and Levenson, 1997), proximity to roads (Gunter et al., 2000; Lo and Yang, 2002), population density (Zipperer, 1993; Lo and Yang, 2002), household density and income (Iverson and Cook, 2000). In the majority of these studies, increased urbanization was associated with loss of total forest area and, where measured, increased forest fragmentation.

Clearing or altering the landscape to accommodate urban structures and processes is usually selective, based on urban needs (Saunders et al., 1991), and generally occurs after a process of planning that may engage people from a variety of public and private domains. Quantitative relationships between changes in specific measures of urbanization over time and changes in the forest over that same time offer powerful tools in planning for and implementing protection of the urban forest resource in future development. However, there are very few studies from which these kinds of quantitative relationships have been produced. In one example of such a study, negative but not significant correlations were found between changes in population density and changes in several forest metrics from 1975 to 1988 in an urban fringe area near Toronto (Puric-Mladenovic et al., 2000). In another study, change in population density between 1973 and 1999 at the level of census tract in the Atlanta, Georgia metropolitan area was the indicator most negatively correlated with change in forest area for this period (Lo and Yang, 2002). The direction and strength of other correlations in this study varied with the spatial scale and parameter or indicator measured.

This is one of a series of studies that was initiated in 2001 to assess changes in the oak forest resource in the TCMA during the 1990's, and to investigate the relationships between these changes and increased urbanization in the TCMA. In the first study, changes in the oak resource of the TCMA for 1991 and 1998 were determined from Landsat TM imagery using ecological subsection (Cleland et al., 1997) as the spatial unit (Ward and Juzwik, 2005; Ward et al., 2006) (Table 1). Overall classification accuracies varied for the different subsections, ranging from 52 to 75% in 1991 and from 56 to 71% in 1998 (Ward and Juzwik, 2005). The authors found that losses of oak area occurred in six of the seven subsections, ranging from 12 ha to over 1200 ha; the area of oak increased by 14 ha in one of the smallest subsections. In a second study, changes in the amount and condition of the oak forest between 1991 and 2000 at the scale of an individual development (from 1 to 70 ha in size) were investigated across several land use classes that varied in degree of urbanization, from undeveloped to industrial (Loeffelholz, 2003).

Table 1
Change in oak forest parameters between 1991 and 1998 for seven ecological subsections of the Minneapolis/St. Paul metropolitan area (Ward and Juzwik, 2005; Ward et al., 2006)

Subsection	Total area (ha)	Percent change					
		Based on[a]	Total area of oak cover	Mean patch density[b]	Mean patch size (ha)	Mean PAR[c]	Mean ENN (m)[d]
Anoka	147,539	1991	−9.08	10.83	−17.97	−7.89	−6.76
		SSa	−0.83				
Big Woods	334,650	1991	−3.44	−8.10	5.07	−6.46	8.83
		SSa	−0.07				
Blufflands	3,819	1991	5.25	20.07	−12.35	−17.76	−9.72
		SSa	0.34				
Mille Lacs	2,884	1991	−3.01	−3.87	0.90	−12.75	5.96
		SSa	−0.42				
Plains	186,199	1991	−3.32	−2.57	−0.77	−9.03	0.86
		SSa	−0.20				
Rochester	24,491	1991	−3.42	0.41	−3.82	−11.84	3.94
		SSa	−0.11				
Savannah	70,655	1991	−6.27	−23.03	23.03	−7.33	16.83
		SSa	−0.07				
Total	770,237	1991	−5.65	−1.19	−4.52	−7.84	1.34
		SSa	−0.25				

[a] For all metrics, change was calculated as a percent of the 1991 value; for area of oak cover, change was also calculated as a percent of the subsection area (SSa).
[b] Number patches/100 ha.
[c] Perimeter to area ratio.
[d] Euclidean nearest neighbor distance.

In the study described here, we quantified urbanization indicators for the TCMA for 1991 and 1998 at the scale of ecological subsection, and then quantified relationships between changes in these urbanization indicators and changes in the oak forest resource, based on the classification and quantification results of Ward and Juzwik (2005) and Ward et al. (2006). Our hypothesis was that increased urbanization would correlate with reduced area and increased fragmentation of the oak forest. Our study adds to the few in which change over time is calculated from measures of both urbanization indicators and forest resource parameters at the same two points in time for the same location. In addition, this is the first study we know of to quantitatively relate urbanization to change in a specific forest type.

2. Methods

2.1. Study area

The “twin” cities of St. Paul and Minneapolis occur at the junction of the Mississippi and Minnesota Rivers in eastern Minnesota. The area we now call the TCMA includes seven counties (Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington) covering a total of 770,000 ha (44°53′N, 93°13′W). The area contains thousands of acres of wetlands and over 900 lakes, as well as a third major river, the St. Croix (Yuan, 2004). Based on a nationwide ecological classification system (Cleland et al., 1997), most of the TCMA lies within the eastern broadleaf forest province which is a transition zone between eastern forest and western prairie (Minnesota Department of Natural Resources, 2006a). A small corner of the northeast TCMA lies within the Laurentian mixed forest province. Within these two provinces, the TCMA includes parts of three sections, the next level of classification, and seven subsections. Subsections are differentiated by soil, geologic, climatic, and natural vegetation characteristics (Keys et al., 1995; Minnesota Department of Natural Resources, 2006a), all of which may have impacted the occurrence of oak forest. Subsection is the unit used for the classification and quantification of the TCMA oak resource on which this study is based (Ward et al., 2006) so subsection is also the spatial unit we used for analysis in this study. The seven subsections are (Fig. 1): Big Woods, St. Paul Plains and Moraines, Anoka Sand Plain, Oak Savannah, Rochester Plateau, Blufflands, and Mille Lacs Uplands (Minnesota Department of Natural Resources, 2006a).

The areas of each subsection within the TCMA boundary range in size from 2800 ha to over 334,500 ha (Ward et al., 2006). The Big Woods, St. Paul Plains and Moraines (Plains; also called the St. Croix Moraines and Outwash Plains), and Anoka Sand Plains (Anoka) cover 87% of the total land area (Fig. 1) and contain 93% of the oak forest area in the TCMA. The ecological subsections are described by the Minnesota Department of Natural Resources (2006a). The Anoka subsection in the north central TCMA is a broad sandy plain with level to gently rolling topography. The western part of the TCMA is in the Big Woods subsection, having level-topped hills and numerous rivers and lakes. The northeast side of the study area is in the Plains subsection, which is characterized by steep, short slopes and many lakes. The remainder of the TCMA contains parts of four other subsections. The Oak Savannah (Savannah) in the southeast has gently rolling topography and few lakes. A small portion of the northeast part of the study area extends into the Mille Lacs subsection where dominant landforms are gently rolling plains with large areas of lakes and wetlands. Much of the southeast part of study area, with its level to gently rolling plains and few lakes, is in the Rochester Plateau subsection (Rochester). Finally, there are two small

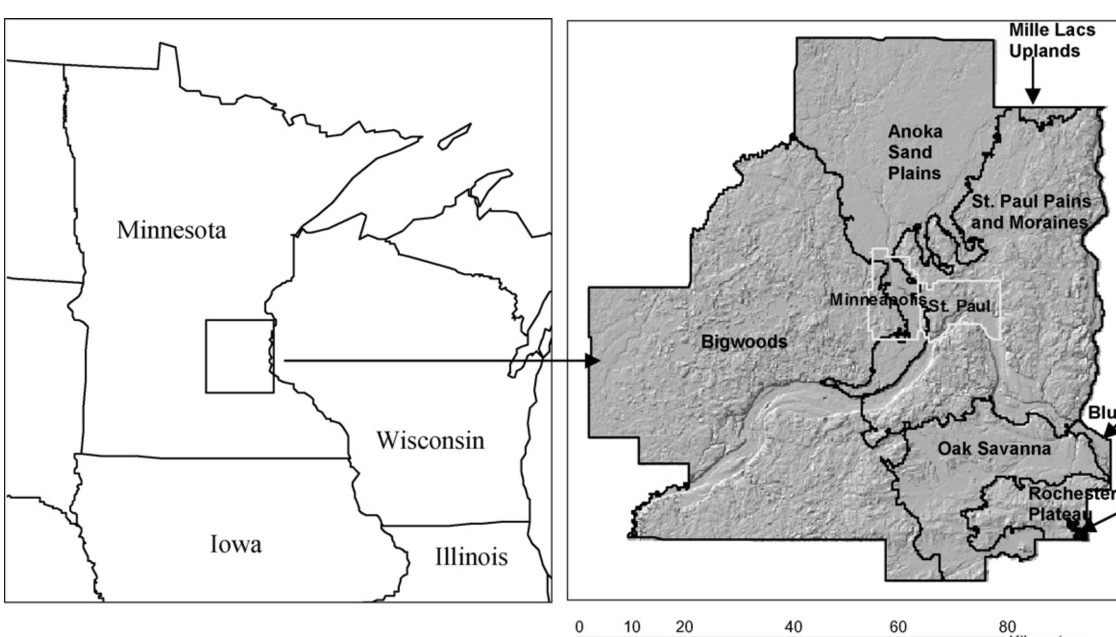

Fig. 1. Location and ecological subsections of the study area of Minneapolis/St. Paul metropolitan area.

areas of the southeast TCMA that are in the Blufflands subsection, which is characterized by many bluffs and deep stream valleys.

2.2. Data

2.2.1. Oak resource

Oak openings along with some mesic hardwood forest and prairie were the major presettlement vegetation types of upland areas in what is now the TCMA (Marschner, 1974). In addition to oak, aspen, red and white pine are major forest types today (Yuan, 2004). White oak (*Quercus alba*), bur oak (*Q. macrocarpa*), northern red oak (*Q. rubra*), and northern pin oak (*Q. ellipsoidalis*) occur throughout the TCMA and are highly valued for landscape and aesthetics and provide important wildlife food and habitat.

Oak forest cover was classified for the TCMA for 1991 and 1998 as described by Ward and Juzwik (2005). The total amount of oak forest in the TCMA decreased by 5.6% (from 33,844 to 31,932 ha) during this period (Ward and Juzwik, 2005). FRAGSTATS (McGarigal and Marks, 1995) was applied to the classification to determine oak patch statistics (Ward et al., 2006). An oak patch refers to a single contiguous stand of oak trees; the subsection average patch size ranged from about 0.3 ha to 1.7 ha (Ward et al., 2006). Estimates of change between 1991 and 1998 used by the authors for each subsection were: total area of oak cover, mean patch density (number of patches per 100 ha), mean patch size, mean distance to the nearest similar patch (Euclidean nearest neighbor distance), and mean patch perimeter to interior area ratio. These were the oak resource metrics used in the analyses for this study.

2.2.2. Urbanization indicators

Indicators used to quantify change in urbanization over time were: area of impervious surface (four different classes), area classified as developed land, and density of human population. Two additional measures, proximity to the nearest road and proximity to the nearest lake or river, were used to characterize spatial patterns of oak stands lost.

Impervious surface refers to areas covered by materials that prevent water infiltration into soil, e.g. pavement covered surfaces and roof-tops of buildings. A positive correlation between increased development and increased percentage of land covered by impervious surfaces has been demonstrated (Arnold and Gibbons, 1996). Classifications of 1991 and 1998 impervious surface area in the TCMA were obtained from Doyle (2004) and Yuan (2004). Relative amounts of imperviousness were classified from 0 to 100% in the original data. The average classification accuracy was 92% (Doyle, 2004). For our study, values were grouped into four classes, the first three of which represent a gradient of imperviousness that has been related to urban stream quality. The quality of a stream is considered “protected” if the watershed is less than 11% impervious, “affected” if imperviousness is 11–25%, and “degraded” if imperviousness is greater than 25% (Schueler, 1994). The fourth class was the total impervious area. Total impervious area (ha) and the area (ha) within the protected, affected, and degraded classes were determined for each subsection for 1991 and 1998 using ArcGIS (ESRI Inc., Redlands, CA), and changes between the two dates were calculated.

Developed land for 1990 and 2000 was determined from the Historical Generalized Land Use data set developed by the Metropolitan Council (2002), the regional planning agency for the TCMA. We defined developed land as areas in the following land use classes: airport, extractive, farmstead, golf course, industrial and utility, institutional, major highway, manufactured housing park, mixed use commercial, mixed use industrial, mixed use residential, multi-family residential, office, railway, retail and other commercial, seasonal/vacation, and single family residential. Undeveloped land was defined as parks and recreation, vacant/agricultural, and public land not developed. Area (ha) of developed land in each subsection was quantified for the two dates using ArcGIS and the changes were calculated.

Population data for the 1990 and 2000 U.S. Census were obtained from Geolytics Inc. (East Brunswick, NJ). Census block group data were imported into ArcGIS and the area and population densities of each block group were calculated. After intersecting ecological subsection boundaries with block group density data, the percent subsection area of each block group was determined. Area-weighted average population densities (people/km^2) were determined for each subsection for 1990 and 2000, and the changes between the two dates were calculated.

Layers to represent all roads in the TCMA and adjacent counties were acquired from the Minnesota Department of Transportation (2005) and J.J. DuChateau (Wisconsin Department of Transportation, personal communication). The numbers of oak patches within three distance-to-road classes (0–500, 500–1000, and 1000–1500 m) were determined for 1991 and 1998 for each subsection and the oak patches lost over the time period were calculated. A similar procedure was used to characterize the proximity of lakes or rivers to oak patches lost. While we do not know of a similar analysis, based on development trends in other areas of the state (Jakes et al., 2003) we expected losses of oak near lakes and rivers to be greater than losses distant from water. Minnesota lakes and rivers data were obtained from the Minnesota Department of Natural Resources (2000). Spatial data for Wisconsin lakes and rivers bordering the TCMA to the east were obtained from the Wisconsin Department of Natural Resources (2003). For lakes and rivers, numbers of oak patches within six distance classes (from 0 to >2500 m in 500 m increments) were determined for 1991 and 1998 for each subsection, and the numbers of oak patches lost over the time period were calculated.

2.3. Statistical analyses

Change in area of oak cover, change in area of impervious surface (all four measures) and change in area of developed land were calculated in two ways (“expression of change”): as a percent of the total subsection area, and as a percent of what was present at the earlier date (1990 for developed land and 1991 for oak cover and impervious surface). For the other measures, we only have values for the two dates, so changes in the oak patch metrics and population density were calculated as the percent of 1991 and 1990 values, respectively. Pearson's correlation procedures were applied to the change values to identify associations between the oak parameters and the urbanization indicators. Where appropriate, regression was applied to further characterize the relationships. All statistics were calculated using the computer program ARC version 1.04, as described by Cook and Weisberg (2002).

3. Results

3.1. Oak resource

For both expressions of change, the Anoka subsection ranked as having the largest decrease in area of oak; rankings of the other five subsections were different for the two expressions of change. Among the patch metrics, inverse relationships and strong correlations were found between changes in mean patch density and mean patch size ($r = -0.944$), and between changes in mean patch density and mean distance to the nearest patch ($r = -0.978$). Change in mean patch perimeter to area ratio was weakly correlated with change in the other oak metrics ($|r|$ ranged from 0.441 to 0.664).

3.2. Urbanization measures

3.2.1. Impervious surface

Between 1991 and 1998, the total area of impervious surface in the TCMA as a whole increased from 26% to almost 32% (Table 2). Expressed as a percent of the subsection area, the greatest increases in total impervious surface area occurred in the largest subsections. Anoka had the greatest change, with 8.1% more of the subsection classified as impervious surface in 1998 than in 1991. Expressed as a percent of the amount of impervious area present in 1991, the greatest increases occurred in the smaller subsections; the Blufflands had the greatest change, with an increase of almost 140%. For 1991, total impervious area in the TCMA was quantified as follows: protected 12% (subsections ranged from 7 to 22%), affected 20% (subsections ranged from 18 to 36%) and degraded 68% (subsections ranged from 41 to 75%) (Fig. 2). By 1998, protected areas decreased in five of the seven subsections and affected and degraded areas increased in all seven subsections.

3.2.2. Developed land

Area of land classified as developed increased in all subsections between 1990 and 2000 (Table 3). As a percent of the subsection area, increases ranged from 1.6 to 7.8, with the greatest increases in the larger subsections. Similar to impervious area, when change was expressed as a percent of the area of developed land present in 1990, the greatest changes occurred in the smaller subsections, and increases ranged from 19.4 to 84.0%.

3.2.3. Population

Average population density increased in every subsection. Increases ranged from 11.6 to 46.7%, with the greatest changes occurring in two of the smaller subsections (Mille Lacs and

Table 2
Percent subsection area (ha) in three impervious surface classes (protected, affected, and degraded) in 1991 and 1998, and the percent change for seven ecological subsections of the Minneapolis/St. Paul metropolitan area

Subsection	Year	Class			
		Protected	Affected	Degraded	Total
Anoka	1991	2.9	6.5	27.9	37.3
	1998	2.0	11.4	32.1	45.5
	Change[a]	−32.3	74.3	15.0	21.6
	Change SSa[b]	−1.0	4.8	4.2	8.1
Big Woods	1991	3.7	4.8	12.7	21.2
	1998	2.3	7.5	16.0	25.8
	Change	−38.2	57.8	26.0	22.0
	Change SSa	−1.4	2.8	3.3	4.6
Blufflands	1991	0.4	0.6	1.3	2.4
	1998	0.5	1.9	3.1	5.5
	Change	17.6	231.8	140.0	139.3
	Change SSa	0.08	1.3	1.8	3.2
Mille Lacs	1991	2.9	4.6	5.3	12.8
	1998	2.3	7.6	7.0	16.9
	Change	−20.2	62.7	31.4	31.0
	Change SSa	−0.6	2.9	1.6	4.0
Plains	1991	3.8	6.7	24.9	35.4
	1998	2.6	10.0	29.0	41.6
	Change	−32.4	49.9	16.4	17.5
	Change SSa	−1.2	3.3	4.1	6.2
Rochester	1991	0.3	0.7	1.7	2.7
	1998	1.0	1.7	2.8	5.5
	Change	269.2	133.2	62.0	101.2
	Change SSa	0.7	1.0	1.1	2.8
Savannah	1991	0.7	2.0	7.4	10.1
	1998	1.4	4.0	9.8	15.2
	Change	94.2	99.9	32.9	50.5
	Change SSa	0.7	2.0	2.4	5.1
Total	1991	3.2	5.2	17.6	26.0
	1998	2.2	8.3	21.2	31.7
	Change	−31.7	61.2	19.8	21.8
	Change SSa	−1.1	3.1	3.5	5.7

Comparisons were based on data from Doyle (2004) and Yuan (2004).
[a] Change calculated as a percent of the 1991 area.
[b] Change calculated as a percent of total subsection area (SSa).

Table 3
Percent subsection area classified as developed in 1990 and 2000, and the change between 1990 and 2000 for seven ecological subsections of the Minneapolis/St. Paul metropolitan area

Subsection	1990	2000	Change[a]	
			1990	SSa
Anoka	32.0	38.2	19.4	6.2
Big Woods	17.9	23.1	29.0	5.2
Blufflands	2.5	4.6	84.0	2.1
Mille Lacs	11.4	14.9	30.7	3.5
Plains	30.5	38.3	25.6	7.8
Rochester	3.5	5.1	45.7	1.6
Savannah	8.6	13.9	61.6	5.3
Total	27.5	34.8	26.6	7.3

Based on data from the Metropolitan Council (2002).
[a] Change was calculated as a percent of 1990 and as a percent of the subsection area (SSa).

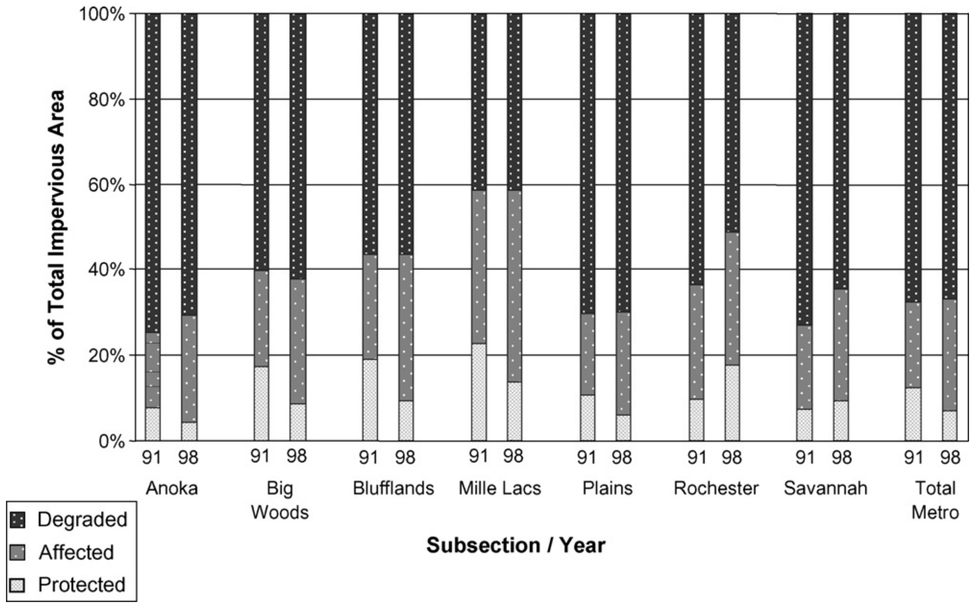

Fig. 2. Percent of total area within three imperviousness classes (protected, affected, and degraded) in 1991 and 1998 for seven ecological subsections of the Minneapolis/St. Paul metropolitan area. Original data were from Doyle (2004) and Yuan (2004).

Savannah) (Table 4). Rankings of the subsections based on population density were the same in 2000 as they were in 1990, with densities ranging from less than 20 people/km^2 in both 1990 and 2000 in the Rochester subsection to almost 500 people/km^2 in 2000 in the Plains and Anoka subsections

3.2.4. *Relationships among urbanization indicators*

Within each of the two expressions of change, change in total impervious area was highly correlated with change in area classified as affected or degraded ($r > 0.900$). Change in area of developed land was strongly correlated with change in total impervious surface area when expressed as a percent of subsection area ($r = 0.847$), and when change was expressed as a percent of 1990 or 1991 ($r = 0.863$). However, the data for the latter were less varied, resulting in a clumping of four subsections when plotted. Change in population density was poorly to weakly correlated with the other measures of urban change ($|r|$ ranged from 0.036 to 0.360).

Table 4
Average population density (people/km^2) in 1990 and 2000 and the change between 1990 and 2000 for seven ecological subsections of the Minneapolis/St. Paul metropolitan area

Subsection	1990	2000	Change[a]
Anoka	447	498	11.4
Big Woods	225	263	16.9
Blufflands	30	33	11.6
Mille Lacs	74	98	32.0
Plains	430	495	15.1
Rochester	14	16	12.1
Savanna	82	120	46.7
Total area	297	343	15.4

Based on U.S. Census data obtained from Geolytics, Inc. (East Brunswick, NJ).
[a] Change was calculated as percent of 1990 density.

3.3. *Relationships between changes in oak and changes in urbanization*

3.3.1. *Area of oak cover*

When change was expressed as a percent of the total subsection area, greater losses in area of oak cover were associated with greater increases in three measures of impervious surface (total impervious area, $r = -0.733$; affected area, $r = -0.836$; degraded area, $r = -0.472$) (Table 5). Correlations were in the same direction but were generally weaker (r ranged from -0.484 to -0.638) when changes were expressed as simply area (ha) (data not shown). The relationship between change in the area of oak cover and change in affected area can be described by the linear regression equation (Fig. 3a):

$$Y = 0.403 - 0.230(X) + \text{error}$$

where Y is the percent of the subsection area that changed in oak cover and X is the percent subsection area that changed to the impervious category of affected ($p = 0.020$). This regression indicates that each percent increase in affected impervious area greater than 2% was associated with a 0.2% loss in area of oak cover. The relationship between change in area of oak cover and change in total impervious area is described by the linear regression equation (Fig. 3b):

$$Y = 0.507 - 0.144(X) + \text{error}$$

where Y is the percent of the subsection area that changed in oak cover and X is the percent of subsection that changed from area with no impervious surface to an area with any amount of impervious surface ($p = 0.06$). Change in oak area and change in area of developed land and change in impervious area classed as degraded were similarly correlated ($r = -0.491$ and -0.472, respectively) when changes were expressed as percentages of the subsection area (Table 5).

Table 5
Pearson's correlation coefficients between changes in urbanization indicators and changes in oak parameters (Ward et al., 2006) in seven ecological subsections of the Minneapolis/St. Paul metropolitan area between 1991 and 1998 (except where noted)

Urbanization indicator	Change based on[a]	Correlation coefficients					
		Area of oak cover			Oak parameters		
		Based on 1991	Based on SSa	Patch density	Mean patch size	Mean PAR	Mean ENN
Population[b]	1990	−0.271	0.020	−0.799	0.849	0.268	0.788
Developed land[b]	1990	0.704		0.167	0.144	−0.646	−0.088
	SSa		−0.491	−0.320	0.163	0.715	0.134
Total area with impervious surface	1991	0.741		0.482	−0.236	−0.805	−0.367
	SSa		−0.733	−0.020	−0.184	0.616	−0.159
Protected area	1991	0.027		−0.149	0.172	−0.166	0.240
	SSa		0.397	−0.145	0.288	−0.371	0.221
Affected area	1991	0.748		0.559	−0.294	−0.802	−0.469
	SSa		−0.836	0.074	−0.306	0.520	−0.214
Degraded area	1991	0.874		0.586	−0.302	−0.871	−0.479
	SSa		−0.472	−0.003	−0.155	0.628	−0.168

[a] For area measurements (area of oak cover, developed land, classes based on impervious surface), change was expressed both as a percent of the area present at the earlier date (1990 or 1991), and as a percent of the subsection area (SSa). For other variables (population, patch metrics), change was expressed only as a percent of the value on the earlier date.
[b] Change calculated for 1990–2000.

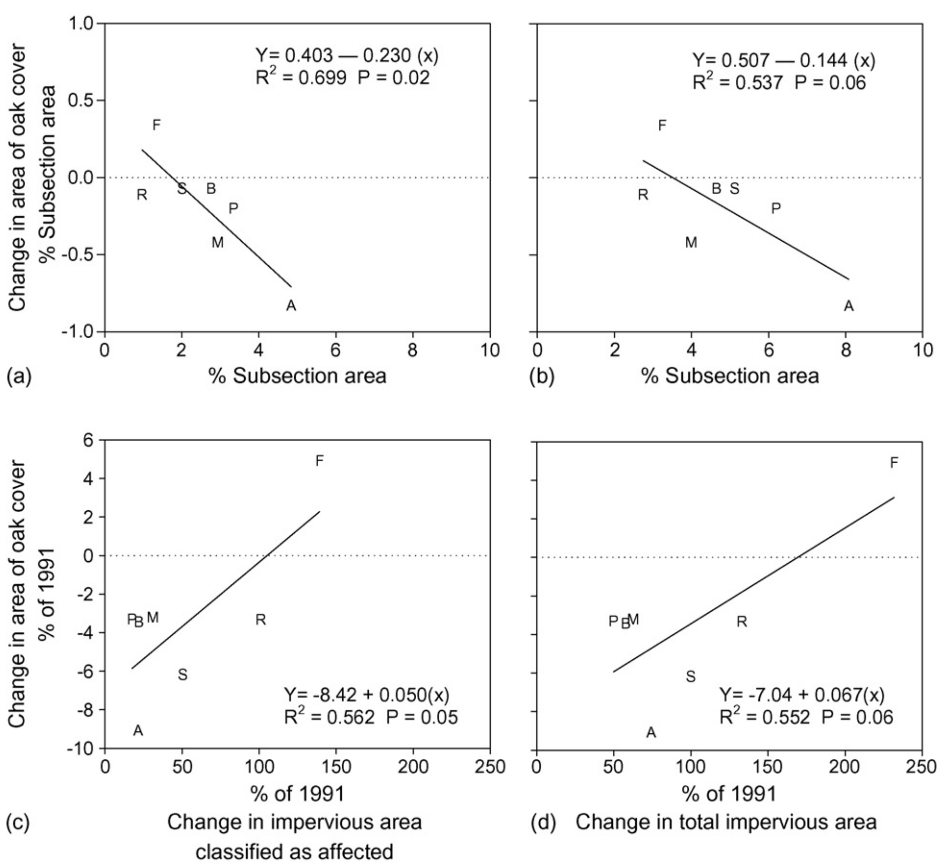

Fig. 3. Relationships between change in area of oak forest and change in area of impervious surface (affected and total impervious surface) between 1991 and 1998 for seven ecological subsections of the Minneapolis/St. Paul metropolitan area. In (a) and (b) change is expressed as a percent of the subsection area; in (c) and (d) change is expressed as a percent of the amount present in 1991. Subsection abbreviations are: B, Big Woods; P, Plains; A, Anoka; S, Savannah; R, Rochester; F, Blufflands; M, Mille Lacs.

When changes in area of oak cover, area of developed land, and areas of levels of imperviousness were expressed as percentages of the amount of each of those areas present at the beginning of the study interval, the quantitative relationships were very different. The direction of the correlations reversed, except for the impervious area classified as protected, for which the correlation coefficient dropped to almost zero (Table 5). Regression equations for two of these relationships are plotted in Fig. 3c and d to allow comparison between the two expressions of change. Population density change was not correlated with change in total area of oak cover expressed as a percent of 1991 ($r = -0.271$) or with change expressed as a percent of the subsection area ($r = 0.020$) (Table 5).

3.3.2. Oak patch characteristics and urbanization indicators

Change in population density was the urban indicator most strongly correlated with three of the four patch metrics (Table 5). Those subsections with the greatest increases in population density had the greatest decreases in density of oak patches ($r = -0.799$), the greatest increases in mean patch size ($r = 0.849$) and the greatest increases in mean distance to the nearest patch ($r = 0.788$). Results suggest that smaller oak patches were completely lost (i.e. attrition) in subsections with the largest population increases, and that the remaining patches had a larger mean size than those that were lost. Mean patch perimeter to area ratio was strongly negatively correlated with total impervious area, affected and degraded areas, and area of developed land ($|r|$ ranged from 0.520 to 0.871) (Table 5) when changes were expressed as percentages of what was present at the beginning of the study. Relationships between change in patch perimeter to area ratio and these same urbanization indicators reversed direction when changes in the urbanization indicators were expressed as percentages of the subsection area. Given that the change in perimeter to area ratio can only be expressed relative to 1991, we suggest that this same expression of change is most appropriate for the urbanization indicators in these relationships.

3.3.3. Oak forest loss and distances to roads, and lakes or rivers

For the subsections in which area of oak cover was lost between 1991 and 1998 (all except the Blufflands), a distance decay function describes the relationship between the amount of oak area lost and distance to the nearest road (Fig. 4a):

$$(Y + 1)^{0.15} = 2.363 - 0.444(X) + \text{error}$$

where Y is the percent of the total area of oak lost and X is the distance to the nearest road, assigned to one of three classes ($r^2 = 0.885$, $p < 0.001$). For most of the subsections, approximately 90% of the total oak area loss occurred within 500 m of a road.

A similar function describes the relationship between the amount of oak area lost and distance to the nearest lake or river for the four subsections (Plains, Mille Lacs, Big Woods, Anoka) that have more than one percent by area occupied by lakes or rivers (Fig. 4b):

$$(Y + 1)^{0.30} = 3.390 - 0.370(X) + \text{error}$$

where Y is the percent of the total area of oak lost and X is the distance to the nearest lake or river, assigned to one of six distance classes ($r^2 = 0.734$, $p < 0.001$).

4. Discussion

Major changes occurred in the TCMA between 1991 and 1998. Urbanization increased and the oak forest was reduced in extent and was transformed in structure. We assume that

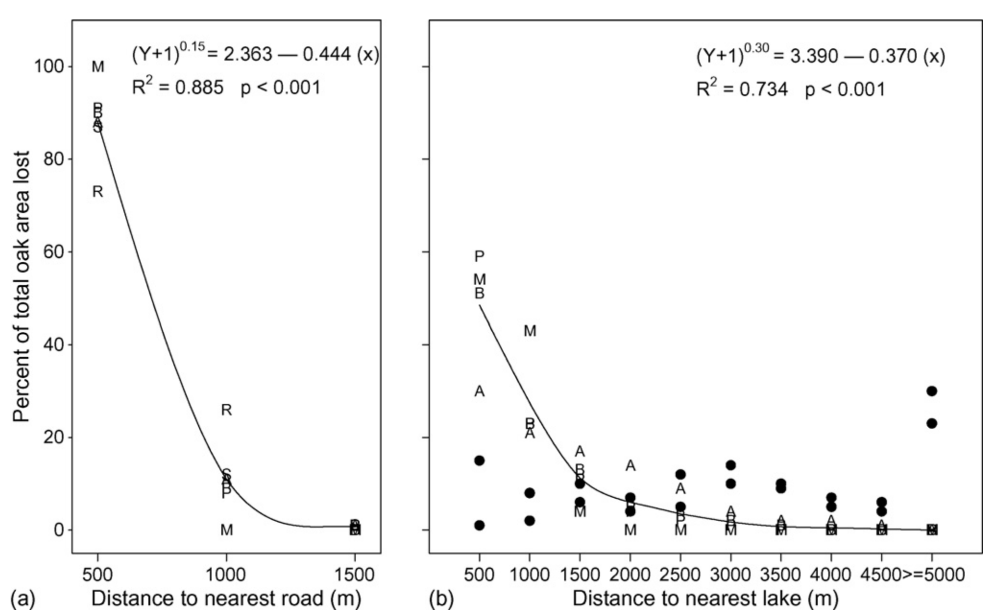

Fig. 4. Percent of total oak area lost between 1991 and 1998 in the Minneapolis/St. Paul metropolitan area and the relationship to (a) distance to the nearest road, and (b) distance to the nearest lake or river. The Savannah and Rochester subsections (●) were excluded from the analyses because they contain few lakes (<1% of the area). Subsection abbreviations are: B, Big Woods; P, Plains; A, Anoka; S, Savannah; R, Rochester; M, Mille Lacs.

diseases and insects contributed to changes in the oak forest, as their damage is often exacerbated by environmental conditions associated with developed woodland sites (Ware, 1982; Houston, 1985; Appel, 1989; Manion, 1991; Kanaskie et al., 1996). With the exception of oak wilt, however, in which infection centers of dead and dying oaks can enlarge year after year if untreated (Juzwik et al., 2004; Minnesota Department of Natural Resources, 2006b), most urban insect and disease disturbances are intermittent in both time and space. Thus, we did not directly address the relationships of insects and diseases to changes in the oak forest, and we made the assumption that tree removal from urbanization was the driving force of oak forest changes across the TCMA.

The most interesting result of this study was the variability among the relationships between urbanization changes and changes in the oak forest. They varied with both the oak parameters and the urbanization indicators. In our study, population density was the urbanization indicator of change most strongly correlated with changes in means of three patch metrics—density, size, and distance to the nearest patch, yet this indicator was only weakly correlated with changes in area of oak forest and mean patch perimeter to area ratio. Increased population density and decreased forest area, and increased population density and increased forest fragmentation were not correlated within the Regional Municipality of York, Toronto, Canada between 1975 and 1988 (Puric-Mladenovic et al., 2000). Correlations reported by Lo and Yang (2002) were −0.480 between increased population density and decreased area of forest land, and 0.320 between increased population density and increased landscape fragmentation at the spatial scale of census tract from 1973 to 1987 in the Atlanta, GA, USA, metropolitan area.

Different parameters capture different elements of the oak resource; area of oak forest, expressed in hectares, is a bottom line measure of amount, while patch metrics, expressed in several different units, provide information about how the forest is configured and distributed across the landscape. At the same time, different urbanization indicators capture different elements of the urbanization processes; areas of imperviousness and developed land, expressed in hectares, provide very different information than population density, expressed in people per unit area. As an example, the number of people who live in a 1.0 ha area with a defined amount of impervious surface can vary widely. The relationship between change in area of developed land and change in area of oak forest may have been stronger if we had used more classes of developed land in the analyses. Within the single class we called developed land there was a wide range of land uses, some having very different impacts on forests than others.

Relationships between urbanization changes and changes in the oak forest also varied with the expressions of change. The negative correlations between change in area of oak forest and changes in areas of imperviousness and developed land were expected. The direction switch that occurred in these relationships when we expressed changes as percentages of what was present at the beginning of the study interval, rather than as percentages of the subsection area, were unexpected. This relationship reversal is related to several factors. To begin with, changes expressed as percentages of what was present in 1990 or 1991 were many times greater than those expressed per unit area for both the oak and urbanization indicators. Second, subsection rankings based on amount of change were different for the two expressions of change. For example, urbanization changes expressed as percentages of the unit area were greater in the larger subsections than in the smaller ones. Changes expressed relative to the amounts in 1990 or 1991 were greater in the smaller subsections than in the larger ones. Third, the re-ranking of subsections for each expression of change in oak area was not the same as the re-ranking of subsections for the each expression of change for a given urbanization indicator.

Another factor contributing to the variability among the relationships of change is spatial scale, which can have a major effect on the quantitative component of urbanization impacts on natural resources (Zandbergen, 1998; Lo and Yang, 2002; Saunders et al., 2002). We would expect that with a finer spatial scale and the resultant increase in data points, the variation among the various urbanization measures of change would decrease. We selected the ecological subsection as our spatial unit because our study began with a focus on the oak resource. We accounted for differences among the subsections in the amount and spatial pattern of the oak forest at the start and end of the study period (Ward and Juzwik, 2005; Ward et al., 2006), but there were also differences within the subsections, particularly the larger ones, that we may not have adequately captured. Similarly, we accounted for differences among the subsections in urbanization at the start and end of the study period, but we may not have captured the variation within the subsections. This was likely to be particularly true for the larger subsections because they encompass both core and first-rings suburbs, where urbanization rates tend to be lower, as well as outer-ring and fringe areas, where rates tend to be higher (MacLean and Bolsinger, 1997; Cifaldi et al., 2004). The smaller subsections (Blufflands, Rochester, Savannah, and Mille Lacs) were largely or entirely located in outer-ring and fringe areas of the TCMA.

To focus on a smaller spatial scale, we divided the TCMA into land type associations which are largely defined by topographic and hydrologic features, as are the subsections, but at a finer level (Minnesota Department of Natural Resources, 2006a). Our sample size increased—the TCMA included all or parts of 25 land type associations, but there was also a much greater range in unit sizes, and the correlations between change in area of oak and changes in the impervious indicators were weaker ($|r|$ <0.30) than at the subsection scale.

Temporal scale is another factor that impacts relationships of change. Forest transformation at a given location occurs in phases (Forman, 1995), the rate and outcome of which are related both to spatial scale and to the length of time over which it is measured (Sharpe et al., 1986). Urbanization also occurs in phases, with the measured rate dependent on many factors (see above), including the interval of measurement. The changes that were measured in the area of oak cover and in the oak patch metrics in this study were most similar to the little or no change that Loeffelholz (2003) found in oak stand size, mean stand area and total oak area in the undeveloped land use class. We suggest that this is reasonable, given that we used the same time interval as Loeffelholz, and that our spatial scale was much larger—in averaging over all land use classes in a subsection, the proportion of undeveloped land may have been sufficient to drive the subsection averages. A lag-time analysis approach may be appropriate for a study such as ours, especially for those scenarios where loss of oak is a result of delayed mortality due to urban related activity.

Two relationships were straightforward—the amount of oak forest area lost and distance to the nearest road, and the amount of oak forest area lost and distance to the nearest lake or river. As we suspected, in the subsections where lakes and/or rivers are common, the majority of oak forest loss (ranged from 51 to 97%) occurred relatively near (within 1000 m) water. Development along lakeshores in outstate parts of Minnesota continues to increase (Jakes et al., 2003), but it appears that lands along lakes and rivers in the TCMA have also attracted development in recent years. Our finding that the majority of oak forest loss occurred near a road (within 500 m) is generally consistent with trends reported by others. Yuan (2004) found that almost half of the new development in the TCMA between 1986 and 2002 occurred within 2 km of highways. Gunter and colleagues (2000) found that distance to a state or federal highway was one of four factors that were significant in estimating the likelihood that a forested tract would be developed; as distance to roads increased by 1 km, the likelihood of development decreased by 42%. Lo and Yang (2002) reported that the proportions of land that were forested were negatively correlated with proximity to roads in 1973, 1987 and 1999 (r ranged from −0.57 to −0.64) and that the change in area of forest land between 1973 and 1999 was weakly positively correlated with road proximity ($r = 0.35$).

5. Conclusions

This is the first published study to quantitatively relate changes in urbanization indicators to changes in a specific forest type within a metropolitan area. Our results suggest that for similar temporal and spatial scales, urban planners can use measures of increased impervious area as a quantitative indicator of the amount of decreased forest area when these changes are expressed as percentages of the total unit area. Increase in the affected class would be the preferred measure, but increase in total impervious area would also be useful. We suggest that change in population density across the landscape may be a useful indicator of how the remaining forest is configured. Change in total area of developed land was not a good indicator of changes in oak forest in our study. Dividing developed land into more specific land use classes in future studies may result in stronger relationships. For the future we also suggest that using a spatial unit smaller than a subsection or one that is based on other boundaries, e.g., administrative may yield quantitative results that are more useful for urban planners and natural resource managers because the units could match their jurisdictions. As urban expansion into rural areas and redevelopment in existing urban areas continue, so will the impacts on oak and other forests; their protection will depend upon an understanding of the complexities of these relationships.

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